IVSS
Intelligent Vehicle Safety Systems

Road Friction Estimation, part II

IVSS Project Report

M. Andersson*, F. Bruzelius, J. Casselgren,
M. Hjort, S. Löfving, G. Olsson,
J. Rönnberg, M. Sjödahl, S. Solyom,
J. Svendenius, S. Yngve

* Contact person, Volvo Technology

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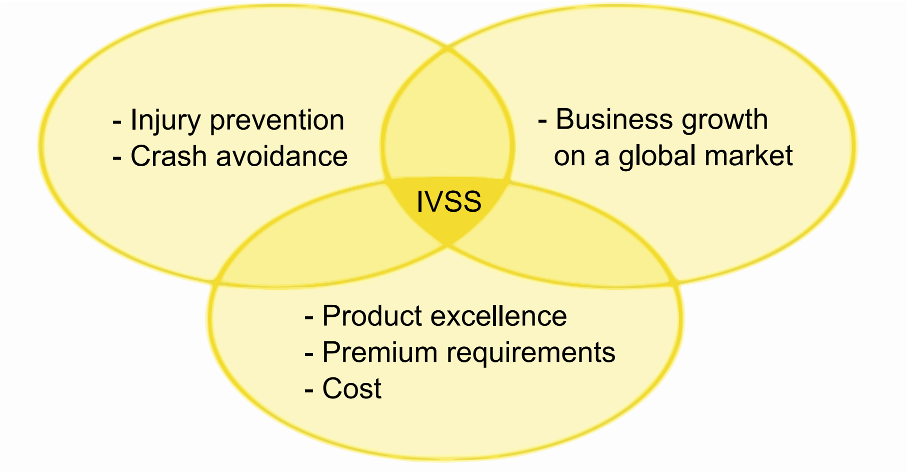
The IVSS Program

The IVSS program was set up to stimulate research and development for the road safety of the future. The end result will probably be new, smart technologies and new IT systems that will help reduce the number of traffic-related fatalities and serious injuries.

IVSS projects shall meet the following three criteria: road safety, economic growth and commercially marketable technical systems.



Three interacting components – for better safety, growth and competitiveness:

The human being

Preventive solutions based on the vehicles most important component.

The road

Intelligent systems designed to increase security for all road users.

The vehicle

Active safety through pro-active technology.

Abstract

This project is part of the Swedish IVSS program. The aim of IVSS is to stimulate research and development of the future road safety . Road conditions with low friction have been identified as a frequent cause of traffic accidents. Therefore, technology to automatically detect changes in road conditions and alert the driver or take proper actions with active driver support systems would be a key contribution to increased road safety.

This project is a continuation of a previous project and aims at further developing the road friction estimator and creating methods for evaluation of such. An investigation was conducted of relevant measures for estimation of the coefficient of friction, resulting in a number of measures. With these measures as a starting point the three methods, from the previous project, based on longitudinal and lateral tire forces and optical properties, were further developed. Both separately and in combination with each other.

For an industrialization to be possible the sensors need to work properly but they also need an end user, hence new and existing applications which could incorporate a friction estimate were suggested and evaluated in the aspect of the above measures.

The three methods separately and in combination have been successfully evaluated, using the developed evaluation method, at proving ground and public road tests in summer and winter conditions with different tires.

Contents

1 Background

Many traffic-safety related investigations prove a correlation between the road condition and the number of accidents. In, for example, [29] it has been shown that the risk for accidents dramatically increases on slippery surfaces. An internal study at Volvo Car Corporation claims that 15 % of all accidents occur owing to low tire-to-road friction. Monitoring of the road conditions is, among vehicle manufacturers, seen as an increasingly important element to support traffic safety. Knowing the coefficient of friction of tire-road interaction it is possible to improve the traffic safety in several ways.

1.1 Road Friction Applications

Several vehicle applications benefit from friction estimation. Below follows a few examples:

1. Road friction information for the driver both directly from the friction estimator in the vehicle and through communication with other vehicles and infrastructure.
2. Autonomous collision mitigation (ACM) functions such as Collision Mitigation by Braking (CMbB) may be enhanced by information about the actual road friction.
3. Enhancement of active safety systems of the vehicle. This includes improved performance of systems such as anti-lock braking system (ABS) and electronic stability control (ESC).
4. Adaptive cruise control with the distance to the vehicle in front automatically adapted to estimated friction
5. Enhanced road maintenance by communication of estimated friction value to the road authorities.
6. Enable the possibilities to; for example, decide speed limits on intelligent roads with variable speed on actual road friction condition.

Different applications have different demands on the quality of friction estimation for example its response time, correctness and availability. These properties are important to take into account when the strategic outlines are made for industrialization of a friction estimator and its applications. For competitive reasons the company which is able to show a well working road friction estimator first will clearly have a great benefit.

1.2 Estimating the Coefficient of Friction

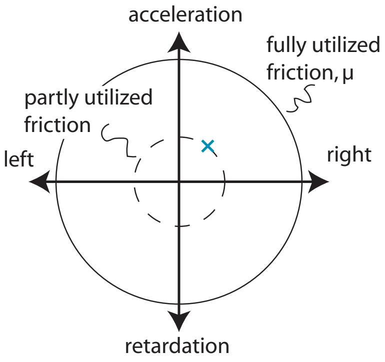


Figure 1: Friction circle

The tire-to-road friction value, μ can be described as the maximum tangential force normalized by the normal force that can be supported between each tire of the vehicle and the road. As such, the friction imposes a limitation on the forces that can be produced by steering, braking, and throttling and is of critical importance to the ability to stabilize the vehicle along a desired path. This limitation can be illustrated by the friction circle, see Figure 1, where the radius of the circle represents the μ-value.

The force utilization is illustrated in Figure 1. During acceleration or braking the force is produced along the vertical axis, during cornering along the horizontal axis, and at combined braking/acceleration and cornering along a direction between the axes. At normal driving the frictional force is not fully utilized and the developed tire force will be somewhere in the interior of the circle. When force is applied to a tire, a relative motion arises between the tire structure and the road. This relative motion is referred to as tire slip. The relation between the resulting tire force and the slip depends on many factors, road conditions, age of the tires, etc., and contains information about the available friction.

Presence of slip or force is referred to as *excitation* of the tire-road friction contact. When the tire is exposed to excitation with high utilization, beyond the point corresponding to the maximum available friction force, the tire is sliding and the resulting tire force directly corresponds to the friction coefficient. For lower utilization, the available friction may be extracted from a model of the tire behavior which is a much more difficult task. Without excitation the friction characteristics cannot be measured directly. In that case an alternative is an indirectly method making a classification of the current road condition mapping it to a coefficient of friction.

In general, methods to estimate tire-road friction can be classified into two groups:

1.2.1 Direct methods

Direct methods are methods that directly addresses the relation between the slip (motion) and the tire forces and tries to estimate the maximum level of tire force that can be applied in the contact patch based on these two quantities. As a consequence, direct methods require a certain level of tire forces (excitation) to operate properly.

1.2.2 Indirect methods

Indirect methods uses an indirect relation to the friction force to determine the coefficient. These indirect relations can be anything from for example wheel house sound to optical measurements of the road surface. The tire to road surface is then estimated as a second step using a priori knowledge on relations to the first indicator, for example using a database.

1.3 Previous Work

The importance of on-vehicle road friction estimation is generally observed and there is a large collection of previous attempts to develop methods reported in patents and scientific articles worldwide, see [21]. The few systems that have found their way to production vehicles are direct methods characterized by either low accuracy and slow convergence, which makes them more of a season detection system, or only functional at very high or full friction utilization like ABS or ESC intervention. Estimation functions aimed at higher availability and accuracy have been proposed that are based on a variety of methods, but still no solution exists up to date.

2 Objectives and Project Scope

In the previous Road Friction Estimation (RFE) project, [17], three different methods for on-line in-vehicle tire to road friction estimation was recommended for further development. The objective of the second RFE project has been to develop a method to objectively evaluate tire to road friction estimators in general and to further improve the three methods from the first project, to bring them closer to an end product. The overall project objectives can be summarized as follows.

- Development and improvement of the three methods from the first RFE project
- Development of an evaluation method for tire to road friction estimators in general
- Validation of the three technologies against the developed evaluation method
- Validation of a combination of friction estimators implemented in the same vehicle against the developed evaluation method
- Evaluation of applications that could benefit from a friction estimation. Vehicle applications, vehicle to vehicle and vehicle to infrastructure applications, the two last in cooperation with the SAFESPOT project
- Industrialisation of the indirect sensor Road eye

The project has involved a wide range of partners from the vehicle industry as well as from Institutes and universities:

- Volvo Technology AB (VTEC), Project coordinator
- Saab Automobile AB (SAAB)
- Volvo Car Corporation (VCC)
- Haldex Brake Products AB (Haldex)
- Optical Sensors (OS)
- Swedish Road and Transport Research Institute (VTI)
- Luleå University of Technology (LTU)
- Lund University (LTH)

The work has been organized into five work packages (WP), dealing with different technologies, methods and applications.

- WP1: Estimation based on lateral forces (SAAB)
- WP2: Estimation based on longitudinal forces (VCC, Haldex and LTH)
- WP3: Estimation based on the optical Road eye sensor (Volvo, OS and LTU)
- WP4: Evaluation method and measures (All)
- WP5: Applications based on friction estimation (All)

WP1-3 has focused on further enhancement of the lateral, longitudinal and optical method within each work package. WP4 have been lead by VTI and focused on evaluation method of tire to road friction estimators in general. The last work package, WP5 have been lead by VTEC and focused on friction applications for both cars and heavy vehicles.

3 Validation Methods and Measures

A method for evaluating tire to road friction estimators have been developed within the project, see [7] for a more detailed description. The objective of this method has been to both be a support in the development of estimators in general as well as, to be used for assessment and decision making within e.g. companies. Hence, a comprehensible method have been developed that is based on six properties that defines good performance, measures based on the properties and a set of test cases that makes the measures unique and defines a metric for evaluating the estimators.

3.1 Properties and Measures

Good performance is defined through five common properties that are easy to relate to and one special property that describes an inherited property of dynamic estimators. The properties are formalized into one (and in some cases two) measures that can be computed based on measurements.

Precision describes the distance of the estimate to the true coefficient of friction. The corresponding measure is defined as a standard RMS value of the estimation error $\varepsilon = \mu - \mu_{ref}$ whenever the estimator consider the estimate confident, expressed by the confidence signal $\hat{\mu}_{conf}$ indicates high validity,

$$\begin{aligned} P &= \sqrt{\frac{\sum_{t=V_\alpha} \varepsilon^2(t)}{\sum_{t=V_\alpha} 1}} \\ V_\alpha &= \{t \;:\; \hat{\mu}_{conf}(t) \geq \alpha\} \end{aligned}$$

Availability indicates how often the estimate is confident with respect to time and/or to environmental conditions. The corresponding measures, force utilization needed η_f and time availability η_t describes the availability of the estimate with respect to force excitation and to time in general (M being the total time). Tire force excitation is clearly associated with direct methods while time availability is more suited for indirect methods.

$$\begin{aligned} \eta_f &= \max_{t \leq t_{req}} \frac{\sqrt{F_x^2(t) + F_y^2(t)}}{\mu_{ref}(t) F_z(t)} \\ \eta_t &= \tfrac{1}{M} \sum_{t=V_\alpha} \Delta t \\ E_\beta &= \{t \;:\; |\varepsilon(t)| \leq \beta\} \\ t_{req} &= \min_t \, (V_\alpha \cap E_\beta) \end{aligned}$$

Response time considers the time aspect of the estimate in terms of how fast a correct estimate can be obtained. The measure of response time is closely related to force utilization needed for direct methods as a certain tire force is always needed to obtain an estimate for these methods. The measure R_s is measuring the distance traveled from a distinct road surface change.

$$\begin{aligned} R_s &= \sum_{t=t_c}^{t_r} v_x(t) \Delta t \\ t_c &= \min_t \, \{t \;:\; |\Delta \mu_{ref}(t)| \leq \delta^{req}\} \\ t_r &= \min_t \, (\{t \;:\; t > t_c\} \cap E_\beta) \end{aligned}$$

Correctness indicates the ability of the estimator to determine when it is correct and not, i.e. a property of its confidence indication. The measure C measures the fraction of time when the estimator both claims to have and have a small estimation error.

$$C = \frac{\sum\limits_{V_\alpha \cap E_\beta} \Delta t}{\sum\limits_{V_\alpha} \Delta t}$$

Robustness is a way of describing how sensitive the estimator is to abnormal situations, e.g. flat tire or very biased sensor information. Each situation will have its own measure, which is the ratio between the normal and abnormal situation regarding precision and correctness.

$$\begin{aligned} R_{precision} &= \frac{P_{Ideal}}{P_{Nonideal}} \\ R_{correctness} &= \frac{C_{Nonideal}}{C_{Ideal}} \end{aligned}$$

Adaptation is the ability of the estimator to adapt to normal but changing conditions, e.g. normal variation of the inflation pressure of the tire or startup conditions in general. The measure A_s is defined as the distance needed to be traveled to recover from a change that affect the estimator error and/or confidence.

$$\begin{aligned} A_s &= \sum_I v_x(t)\Delta t \\ I &= V_\alpha \cap E_\beta \end{aligned}$$

It should be noted that these measures are not uniquely determined merely on the expressions above, even with given thresholds (e.g. α, β). A test case, specifying the environmental conditions and, for the direct methods, a tire force trajectory is needed in order to form an evaluation method.

3.2 Test Cases and Conditions

It should be clear from the previous section the importance of a reference value of the friction, as all measures are based on the estimation error between the estimate and some reference. Hence, the quality of the reference will directly affect the quality of the evaluation. For practical reasons it is not always possible to make rigorous reference measurements and one have to rely on e.g. in-vehicle accelerometer, ABS systems and the assumption of homogeneous test surfaces.

Test cases can be divided into cases specifically designed for direct methods where the tire force is of central importance and more general cases. Example of cases designed for direct friction estimation methods is tire force ramps, where the acceleration (laterally/longitudinally or both) is increased in a linear manner. This case is very well suited for the 'force utilization needed' measure. Another test case for direct methods is so called varying force excitation, e.g. stepwise force changes (panic braking, panic steering) or slalom steering and/or braking/accelerating calmly.

An example of a more general test case is a stepwise change of road surface, e.g. from tarmac to gravel or wet tarmac to icy tarmac. This test case is of importance together with the time response measure to evaluate the speed of the estimator. Another class of test cases of general type is longer driving tests on public roads such as rural or urban driving. Longer driving test cases are of interest to benchmark real life performance. Even though longer test cases on public roads are hard to reproduce, it may serve as a comparative study between two estimator approaches or to reveal true weakness of one single approach.

A last example of a test-case class is the one dedicated to measure the sensitivity to abnormal situations, i.e. to the robustness measure. These test cases are typically short and with a focus of reproducibility, as the robustness measure is defined as the fraction between ideal conditions and non-ideal conditions of the precision and correctness measures. The abnormal non-ideal situations are determined by the specific estimator, e.g. road dirt in the optical path of a optical based estimator or flat tire for a direct method estimator.

4 Estimation Based on Longitudinal Forces

A longitudinal force based friction estimator is active during longitudinal tire force excitations such as braking or throttling. The estimator concept used here relies on a physically derived tire model called the brush model, see e.g. [25]. In its simplest formulation the model describes the relationship between the tire force and the slip as a function of two parameters, the tire stiffness and the tire to road friction coefficient. The tire stiffness describes the inclination of the force-slip relation at small slips whereas the friction coefficient describes its curvature and peak value.

Previous publications have shown that there is a correlation between low tire stiffness and low friction coefficient. Methods have been developed to determine tire to road friction from estimates of the tire stiffness alone. Those methods have shown to be unreliable since this correlation is unpredictable and changes with e.g. tire wear, temperature and tire type.

The proposed concept suggests estimation of both the tire stiffness and the friction coefficient to make the estimation more reliable and accurate. The drawback is that it requires higher forces acting on the tires and a more complex estimation algorithm. Identification of two parameters compels higher demands on availability of measurement data. Data must be available in a large enough area of the force-slip plane such that it contains information about both the inclination and the curvature of the tire force-slip relation.

In the previous work performed in IVSS-RFE I two approaches suitable for this purpose were proposed. Both methods have been refined and improved during this project. Items that have been considered most important to improve are

- Extend working range to include simultaneous lateral and longitudinal tire forces
- Improve surface change detection to speed up estimator.
- Develop a confidence measure

Work has also been done to improve signal quality and to reduce the computational effort and need of vehicle reference speed.

4.1 Approach

The two previously developed methods have been refined and improved. The methods are characterized as

- **The bin method**. An algorithm based on storing data points in the slip-force plane in discrete bins. These points are used to compute the tire stiffness and the tire to road friction by non-linear least squares optimization. It inherently handles clustering of data in periods where the vehicle is subjected to constant excitation.
- **Grid-rls**. In RFE I the grid-method used a two dimensional discrete grid of the tire stiffness and the friction coefficient. The method became very memory consuming. The major improvement done is to combine a grid with a linear regression method. The friction coefficient is discretized at a number of levels and the method estimates the tire stiffness running several recursive least squares (RLS) filters in parallel. The improvement increases the accuracy and robustness and reduces the computational effort significantly.

4.1.1 The brush model

The main idea behind the brush model is that the tire surface area in contact with the road can be modeled as independently deformable infinitesimal bristles. In one part of the contact zone the bristles transfer force by mechanical adhesion. In the other part the bristles are sliding on the road and giving a frictional force based on assumption of coulomb friction and parabolic vertical pressure distribution. The friction is assumed to be isotropic, i.e. equal in both longitudinal and lateral directions.

The standard appearance of the brush model for describing the tire forces as a function of tire parameters and the slip in longitudinal direction is

$$F(\sigma, C_0, \mu) = \begin{cases} -\sigma\, C_0 + \dfrac{\sigma\ |\sigma|\ C_0^2}{3\,\mu} - \dfrac{\sigma^3\, C_0^3}{27\,\mu^2} & \text{if} \quad |\sigma| < \sigma^\circ \\ -\mu \text{sign}(\sigma_x) & \text{otherwise} \end{cases} \tag{1}$$

with $\sigma^\circ = 3\mu/C_0$. When including simultaneous lateral tire excitation in the model, dependence of the lateral slip should preferably be avoided of measurement reasons. In [5] it is shown that the following signal transformation can be done to include the lateral effect on the longitudinal properties

$$F = f_x \sqrt{\frac{f_y^2}{f_x^2} + 1}; \qquad \sigma = \sigma_x \sqrt{\frac{f_y^2}{f_x^2} + 1} \tag{2}$$

The reformulation has assumed isotropic tire stiffness. Due to the limited validity of and for numerical reasons, the model is assumed to be valid only in a limited sector in the (f_x, f_y)-plane, i.e. $|\frac{f_y}{f_x}| < \phi_{lim}$

4.2 Results

Information about the road friction coefficient is only available when the measurements of the slip-force curve show curvature. This requires a particular amount of friction utilization. Internal studies done within the project [21] show that about 80 % of friction utilization is required to get reasonable accuracy on the estimate. The test result presentation in Section 8.2 confirms the picture that about 80 % is required to get an estimate with high confidence.

Examples of estimator results on snow and asphalt are shown in Figure 2. On asphalt the estimates never obtain high confidence because of insufficient utilization (the normalized tire force is at maximum 0.5 and the friction is about 1.1) and no curvature of the force-slip relation can be observed. Lack of curvature makes the estimate go toward infinity but for physical reasons it limited to 1.2 and the results becomes reasonable.

The two proposed algorithms perform similarly at ramp excitation.

The combined slip extension improves the estimator behavior particularly at higher combined slips and specially at high forces utilization. At lower slips the extension introduce noise, which sometimes has a negative effect on the results.

The road friction estimators need input of longitudinal tire slip and normalized lateral/ longitudinal forces. High levels of utilization contain more information about the road friction but high utilization occurs rarely. The goal is to get a quick estimator which responds quickly to short periods of high utilization but that requires very high signal quality. The estimation process of those signals introduce noise which is not negligible. The wheel speed is, for example, quite accurately measured, but do not always coincide with the tire peripheral speed and the road surface, due to the tire and suspension dynamics. The vehicle reference speed that is necessary for the slip calculation is difficult to derive with satisfactory accuracy when all four wheel speeds are affected by tire forces. The forces acting on the tires, derived either from accelerometer sensors, from engine or brake information are tiled with reliability problems. This inevitably results in estimators that require longer periods of high force utilization.

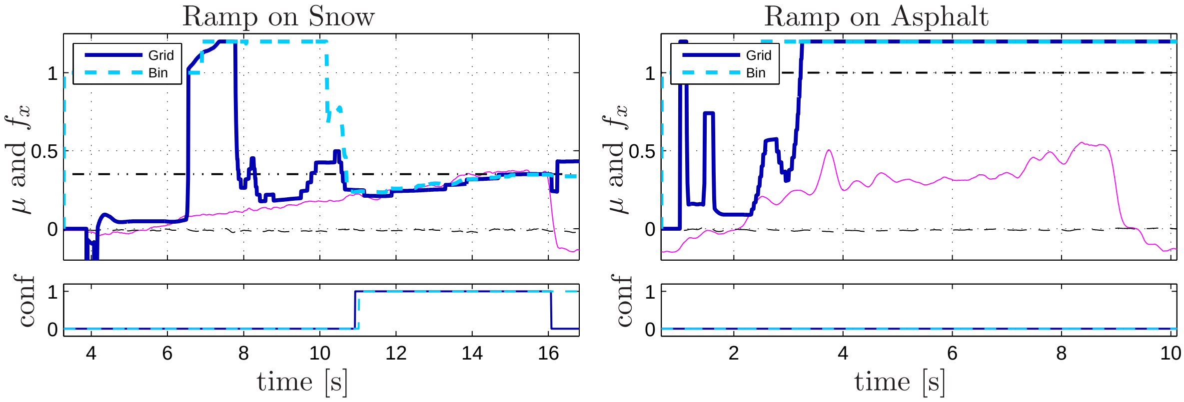


Figure 2: Left plot shows estimation results for ramp-force excitation on snow. Right plot shows the results on asphalt. The thick dashed show the μ estimate from bin method and thick solid the μ estimate from grid-rls method. In the upper plots the thin solid line shows normalized longitudinal force $f_x = F_x/F_z$, the thin dashed line shows normalized lateral force $f_y = F_y/F_z$ and the dashed-dotted show surface reference friction. The lower plots show the confidence measure for each method.

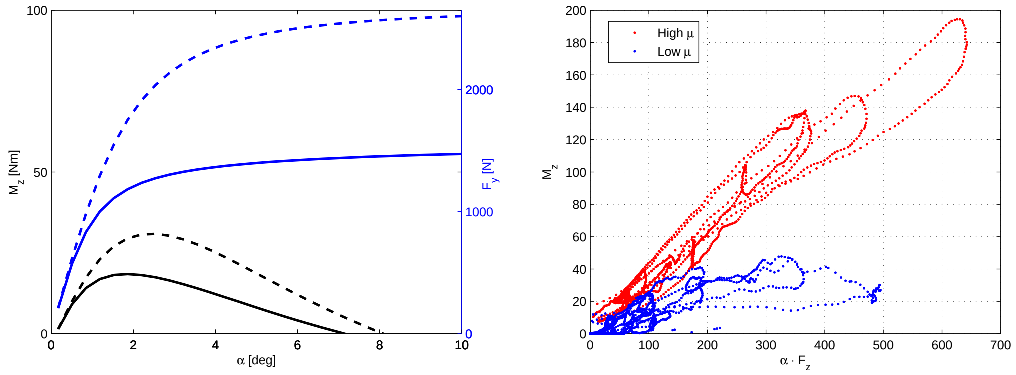


Figure 3: Lateral Force and Self Aligning Torque on snow and wet asphalt

5 Estimation Based on Lateral Forces

The lateral force based friction estimator is active during lateral force excitation, i.e. when the vehicle is turning. The estimation is based on the tire self aligning torque. As seen in the left plot of Figure 3 the self aligning torque (SAT) shows a more non-linear behavior at lower slip angles compared to the lateral force. Therefore it is possible to estimate the tire road friction coefficient for lower levels of utilization if SAT is used as a basis for the estimator instead of the lateral force. Even for low slip angles the slope of the SAT curve on high μ is higher compared to the slope for the SAT on low μ. The curves in the left plot in Figure 3 are based on theoretical relationships while the right plot is based on measured SAT. The SAT is plotted against the side slip, α, multiplied with the normal force, F_z. In real measurements, the initial slope difference seems to be a clear indicator of the tire road friction coefficient.

5.1 Approach

To broaden the operating area of the lateral estimator the calculation of SAT needs to take the effects of combined lateral- and longitudinal slip into account. This is done by using the extended brush model according to

$$M_{z,total} = M_{z,lat} - cF_xF_y - F_xv_0. \tag{3}$$

The measured SAT is $M_{z,total}$. To compensate for combined slip an equivalent pure M_z is calculated based on the measured M_z, estimated F_x and F_y;

$$M_{z,equiv} = M_{z,meas} + cF_xF_y + F_xv_0 \tag{4}$$

where c is the so called compliance coefficient and v_0 is the initial lateral offset of F_x see e.g. [18].

The main idea with the continuous estimation algorithm is to identify the SAT characteristics and then map that to a tire road friction coefficient. As identification parameter the initial linear slope as seen in Figure 3 is used. Since the SAT curve is linear only for low slip, a second algorithm is estimating the partial derivative of the SAT curve thus preventing the slope identification algorithm from making wrong estimations when the non-linear region is entered. The estimation is based on the following equation

$$M_z = k_{slope} \cdot \alpha \cdot F_z. \tag{5}$$

The partial derivative estimation is based on

$$k_{op} = \frac{\partial M_z}{\partial \alpha \cdot F_z} \Rightarrow \frac{\partial M_z}{\partial t} = k_{op} \cdot \frac{\partial \alpha \cdot F_z}{\partial t} \tag{6}$$

When a valid slope has been identified the value of k_{slope} needs to be converted to a corresponding tire-road friction coefficient. This is done using a look up table with estimated k_{slope} as input and tire-road friction μ as output. The look up table needs to change depending on the tires so an adaptive look up table is preferred . The adaptation is done using minimum and maximum friction limits also based on the self aligning torque [17]. Minimum friction limit is calculated as

$$\frac{M_z}{M_{z,nom}} = 1 - \frac{\sqrt{F_y^2 + F_x^2}}{\mu_{util} \cdot F_z} \Rightarrow \mu_{min} = \frac{\sqrt{F_y^2 + F_x^2}}{F_z\left(1 - \frac{M_z}{M_{z,nom}}\right)} \tag{7}$$

Maximum friction limit is calculated as

$$\mu_{max} = 1 - \frac{M_{z,nom} - M_z}{(\Delta M_z)_{max}} \left(1 - \frac{\sqrt{F_y^2 + F_x^2}}{F_z}\right) \tag{8}$$

5.2 Results

Results from the self aligning torque based friction estimator are presented in Figure 4. The top plot shows a steering ramp from zero force utilization to full force utilization on snow with winter tires. The middle plot shows a run with varying lateral excitation on snow with winter tires and the bottom plot shows the same excitation but on asphalt with summer tires.

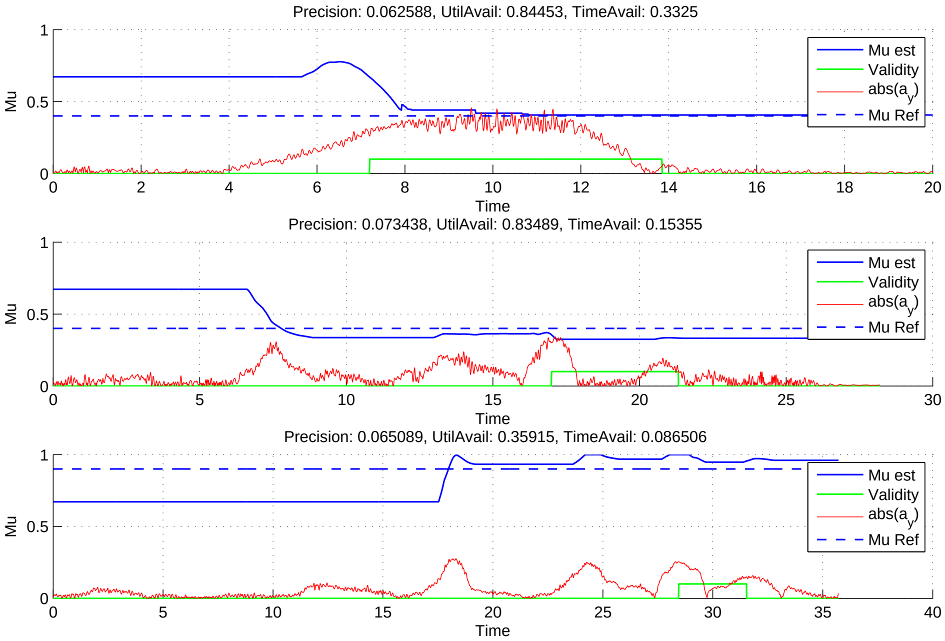


Figure 4: Estimation results showing $\hat{\mu}$, μ_{ref}, confidence signal (Validity) and $abs(a_y)$

6 Estimation Based on the Optical Sensor Road eye

In the previous RFE I project it was shown that the optical sensor Road eye [16] had potential classifying different phases of water (ice, snow and their mixes), due to different resonance frequencies at near infrared wavelengths (1-2 μm). Although the overall test showed promising there were some difficulties classifying some conditions of wet asphalt from icy asphalt. Hence, the aim in this second part of the RFE I project was to solve this problem. Further, road surface roughness is an important parameter determining road friction correctly. Therefore a model of light reflection from soils was applied to the Road eye measures estimating the porosity and the roughness of each road condition.

6.1 Approach

To solve the problem of classifying some conditions of wet asphalt from icy asphalt a third laser was mounted into the Road eye sensor. The idea of the third laser, with a different wavelength than the previous two, was to increase the reflected intensity. Therefore a wavelength with the lowest absorption coefficient for water, snow and ice within the bandwidth of the photo diode was chosen. The increased intensity was assumed to increase the differences between the water and ice reflectance and thereby enhance the classification. This assumption was first verified in laboratory tests in a controlled environment with homogeneous surfaces with known depths and then tested on actual road conditions.

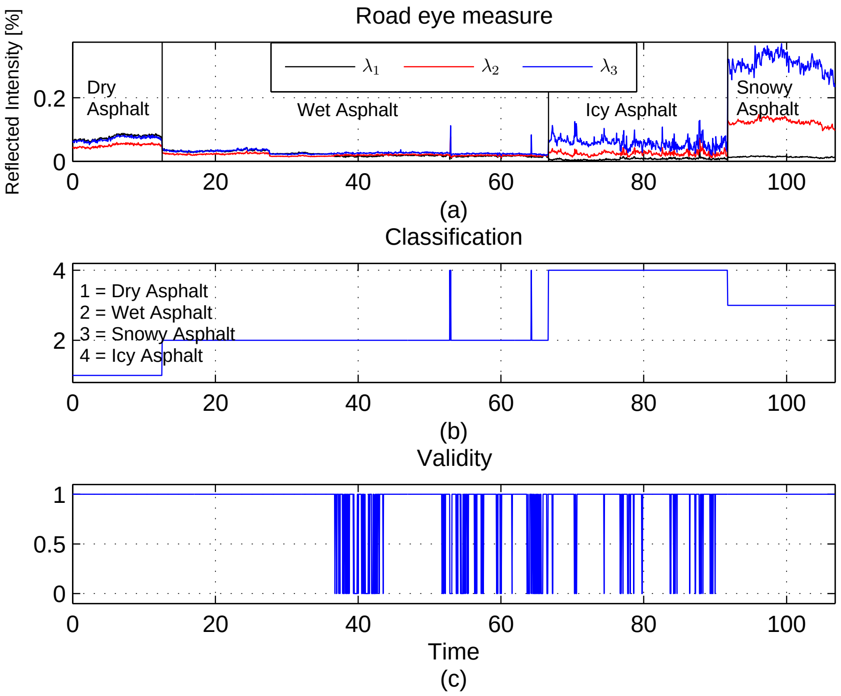


Figure 5: a) Raw data from the Road eye sensor for the four road conditions(Dry, wet, icy and snowy asphalt). b) The classification of the four road conditions. c) The validity of the classification.

6.1.1 Algorithm

The classification algorithm builds on the assumption that ratios between two wavelengths will stay the same as long as the road condition is the same, i.e. independent of intensity changes caused by for example new and old asphalt. By introducing the third wavelength at least two intensity independent variables could be calculated from the Road eye outputs $\lambda_1[n]$, $\lambda_2[n]$ and $\lambda_3[n]$ (see Figure 5 a). From the output the variables $\theta[n]$, $\phi[n]$ and $r[n]$ were calculated as:

$$\theta[n] = \arctan(\frac{\lambda_1[n]}{\lambda_2[n]}), \phi[n] = \arctan(\frac{\lambda_3[n]}{\sqrt{\lambda_1[n]^2 + \lambda_2[n]^2}}), r[n] = \sqrt{\lambda_1[n]^2 + \lambda_2[n]^2 + \lambda_3[n]^2} \quad (9)$$

where θ and ϕ are intensity independent variables and r is the total reflected intensity. The variables were then implemented into the classification algorithm which was based on the K-mean cluster [28] algorithm. The output from the algorithm was a classification (see 5 b) and a validity (see 5 c). The validity is 1 if the Euclidean length in the K-mean cluster is inside 80 % confidence interval. Bidirectional reflectance spectroscopy have been an intense research area for planetary observations [11, 12, 20, 10] determining surface soil content of planets. As soil and asphalt are similar in composition and substances the developed model for soil was within this project applied on the different road condition which all have a foundation of asphalt. The model is based on the radiative transfer equation [9] and describes the reflected intensity from a surface compared with the reflectance from a Lambertian/diffuse surface. The bidirectional reflectance (r) is given by:

$$r(\mu_0, \mu, g) = \frac{w}{4\pi} \frac{\mu_0}{\mu_0 + \mu}([1 + B(g)]P(g) + H(\mu_0)H(\mu) - 1) \tag{10}$$

where μ_0 is the cosine of the inclination angle ($\mu_0 = \cos(i)$) of the impinging light, μ is the cosine of the reflectance angle ($\mu = \cos(e)$) of the reflected light and g is the phase angle (the angle between i and e). Further, $P(g)$ describes the angular distribution, $B(g)$ is a function describing the roughness of the surface which becomes 1 for a perfectly smooth surface and last the term $H(\mu_0)H(\mu) - 1$ which approximates the contribution from the multiple scattering inside the surface medium. As in [12, 20, 10] a non linear least square fitting procedure was used to solve the inverse modelling problem. The estimation was done using the MATLAB function 'lsqnonlin', implementing the Levenberg-Marquardt method. The estimation was carried out against each wavelength respectively.

6.2 Results

The test results are shown in Figure 5 a) where the raw data for the four different road conditions, dry, wet, icy and snowy asphalt are depicted. The result from the classification algorithm is shown in Figure 5 b) which agrees well with reality. There are only three points were the classification is wrong and this is due to road markings. Figure 5 c) depicts the validity and it can be observed that based on the validity there are more samples then three that are not trustworthy, with an 80 % confidence interval approximately 7 % is under the acceptance level.

The results of the estimation of $P(g)$, $B(g)$ and $H(\mu)$ is shown in Figure 6. As seen in Figure 6 a) and b) the P and B functions gives a good estimation of the surface roughness. P is high for dry asphalt and snow and low for water and ice and the opposite for B. The H function depicted in Figure 6 c) also shows promising results estimating the porosity of the surface. The surface roughness and the porosity of a surface are two parameters closely connected to the friction coefficient of a surface. These parameters therefore would give a much better translation of a classification of a road condition to a friction value, than the look up table that was used in previous project. The next step would be to thoroughly investigate the connection between the roughness and porosity parameters and the friction coefficient.

7 Integrated Friction Estimation

Integration of the three different concepts proposed has potential to provide an even better road friction estimate. An attempt has been done to combine the both force based approaches and a suggestion how to integrate the indirect optical method with the force based methods is proposed.

7.1 Combination of Force Based Methods

The two force based approaches are inherently limited to operate during either longitudinal- or lateral excitation, i.e. during acceleration/braking or cornering respectively. In Figure 7 it can be seen that algorithms are active, for the most part, only one at a time. Since they are active during different parts of the driving it opens for the possibility of combining the two to improve the road friction estimation performance and availability.

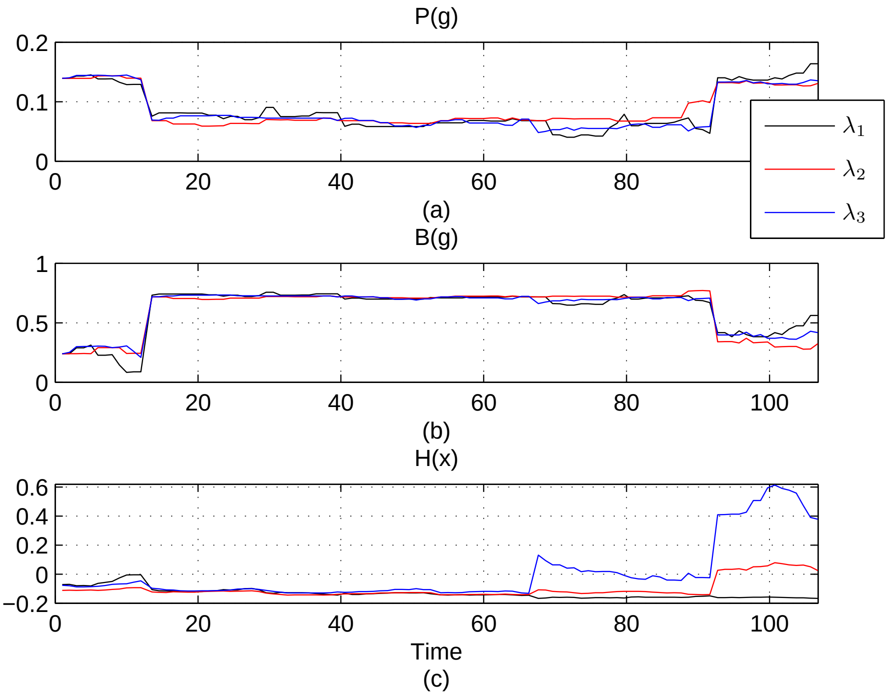


Figure 6: a) $P(g)$ describing the angular distribution. b) $B(g)$ explaining the backscattering of light. c) $H(\mu_0)H(\mu) - 1$ approximating the contribution from multiple scattering.

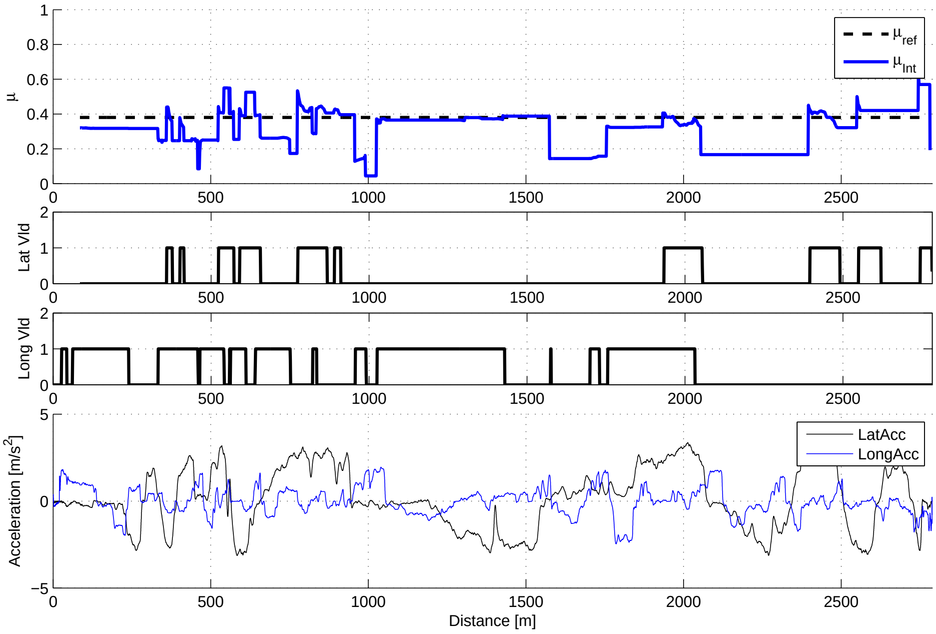


Figure 7: Integrated longitudinal and lateral friction estimation.

A basic approach of integration is to treat the two force based algorithms as independent and use a third algorithm to fuse the information. In Figure 7 the fusion algorithm uses the confidence information from the two algorithms.

$$\hat{\mu}_{fus} = \frac{\hat{\mu}_{conf}^{long}\hat{\mu}_{long} + \hat{\mu}_{lat}\hat{\mu}_{conf}^{lat}}{\hat{\mu}_{conf}^{long} + \hat{\mu}_{conf}^{lat}}, \qquad \hat{\mu}_{conf}^{long} + \hat{\mu}_{conf}^{lat} \neq 0 \tag{11}$$

If only longitudinal excitation is present and the longitudinal algorithm has a confident estimate the fusion algorithm uses this as the final estimated value. If both lateral and longitudinal excitation is present at the same time and both algorithms have confident estimates, the mean value is used. The algorithms in Figure 7 output only binary validation flags but (11) can also be used with continuous confidence signals.

7.2 Integration of Optical Sensor Road eye

Besides from integrating different force operating areas it would also be possible to integrate the Road eye sensor in the fusion algorithm. Further the two proposed force based algorithms uses memories which can be cleared whenever Road eye detects a sudden surface change. That in combination with new good initial guesses obtained using the Road eye estimate would significantly speed up convergence toward new valid estimates.

In turn the force based methods can be used to update the look-up table which Road eye uses to relate optical properties to road friction. If a particular surface is identified by Road eye and the force based algorithm obtains a valid road friction estimate the look-up table used by Road eye is updated accordingly.

8 Experimental validation

This section presents the experimental validation of the estimators using the measures defined in previous sections. Experimental validation was also conducted for a tire model used in one of the friction estimators, the one based on longitudinal tire forces.

8.1 Tire Measurements

One of the objectives of this project was to extend the validity domains of the force based estimators of the first phase of the RFE project, see [17], to cover combined slip situations. Combined slip is when the lateral and longitudinal forces are present in the contact patch simultaneously. To support this development a number of measurements of tire characteristics were performed with the BV12 measurement vehicle, see Figure 8. The measurements were conducted on some typical road surfaces in Sweden. Three different types of tires that represent a wide variety of tire characteristics and also tire types that are common on Swedish roads were tested in the measurements, see Figure 9. The measurements has been used to validate a derived tire model to be used in the friction estimators, see [5].

8.2 Estimator Validation

In this section the measures, defined in previous sections, is used to benchmark the three different approaches of the project. This study and the result is further described in [7]. Two main scenarios have been the objectives of the testing; the tire force excitation ramp and

Figure 8: The mobile tire tester B12 operated by VTI

Figure 9: List of test conditions of the BV12.

Tire type	**Road surface**	**Load**	**Side slip angle**
Winter	Wet tarmac	2,4,6 kN	0,1,3,5,10
Winter	Gravel	4 kN	0,1,3,5,10
Winter	Ice	4kN	0,1,3,9
Winter	Packed Snow	4kN	0,1,3,9
Summer	Wet tarmac	2,4,6 kN	0,1,3,9
Summer	Gravel	2,4,6 kN	0,1,3,9
Studded	Wet tarmac	2,4,6 kN	0,1,3,9
Studded	Gravel	4 kN	0,1,3,9
Studded	Ice	2,4,6 kN	0,1,3,9
Studded	Packed Snow	2,4,6kN	0,1,3,9

Table 1: List of test cases and their corresponding descriptions.

Test	**Type**	**Appl.**	**Surface**	**Tire**	**Comb. slip**	**Disturb.**	μ_{ref}^{long}	μ_{ref}^{lat}
#1	Force excit. ramp	slow	Ice	Winter	None	None	0.12	0.16
#2	Force excit. ramp	slow	Ice	Winter	Low	None	0.12	0.16
#3	Force excit. ramp	slow	Snow	Summer	None	None	0.18	0.25
#4	Force excit. ramp	slow	Snow	Summer	Low	None	0.18	0.25
#5	Force excit. ramp	slow	Snow	Studded	None	None	0.4	0.45
#6	Force excit. ramp	slow	Snow	Studded	Low	None	0.4	0.48
#7	Force excit. ramp	fast	Snow	Studded	None	None	0.35	0.46
#8	Force excit. ramp	slow	Snow	Winter	None	None	0.35	0.4
#9	Force excit. ramp	slow	Snow	Winter	Low	None	0.35	0.4
#10	Force excit. ramp	slow	Snow	Winter	High	None	0.35	0.4
#11	Force excit. ramp	fast	Snow	Winter	None	None	0.35	0.4
#12	Force excit. ramp	slow	Snow	Winter	None	High infl. press.	0.35	0.4
#13	Force excit. ramp	slow	Snow	Winter	None	Low infl. press.	0.35	0.4
#14	Stepwise excit.	slow	Asphalt	Summer	None	None	1.0	0.9
#15	Stepwise excit.	fast	Asphalt	Summer	None	None	1.0	0.9
#16	Stepwise excit.	slow	Asphalt	Winter	None	None	1.0	0.8
#17	Stepwise excit.	fast	Asphalt	Winter	None	None	1.0	0.8
#18	Stepwise excit.	slow	Snow	Winter	None	None	0.35	0.4
#19	Stepwise excit.	fast	Snow	Winter	None	None	0.35	0.4

the stepwise excitation. The particular choice of these two scenarios is motivated by that direct methods depend on a specified tire force trajectory like stepwise excitation or force ramp as a test case. The indirect method of the project, the Road eye, does not need any specific excitation or driving scenario and can hence use the two test cases as well. Combined slip scenarios are explicitly addressed in the test cases as one of the project objectives was to extend the two direct method estimators to handle this. Two test vehicles were used; one Volvo S80 and one SAAB 9-3, both equipped with a Road eye sensor, and with similar tires; winter (unstudded), summer and studded tires. The test cases are listed in Table 1. A longer test case was also conducted on a public rural road. Public rural roads does not have a homogeneous surface and the driving style must be adapted to the present traffic conditions. Hence, this test case is not suited as a base for absolute measures comparing different approaches. Only one test vehicle data is presented here.

The test results are summarised in Figure 10 and 11. The missing results for the direct method based estimators is not a performance weakness but a lack of tire force excitation in the test scenario. The indirect method based estimator, the Road eye, was not in operation for the test cases where there are no result in the two figures. It should be noted that the Road eye

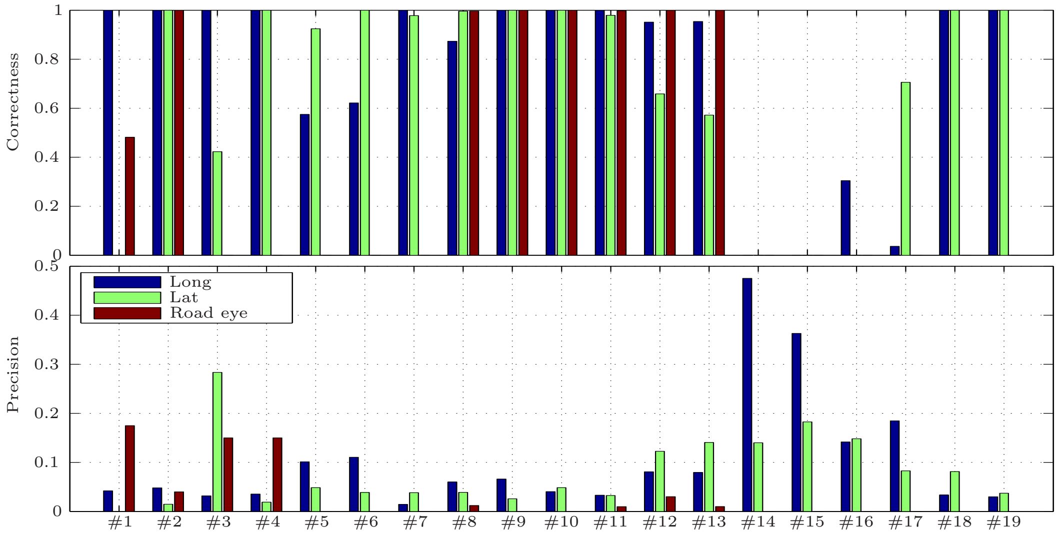


Figure 10: The precision measure for the test cases (bottom) and the correctness measure (top). Note that for precision a low value is good and for correctness a high value is good

estimator does not have a mechanism that updates the mapping between the road classification and tire to road friction. In the test cases presented here, this mapping was corrected manually. This implies that the estimation error was small whenever road classification was correct. Further more, this implies that the measures indicates a higher performance than in the normal case with a mapping that is not up to date, as in real life.

The precision measure

The computed precision measure is depicted in the lower plot of Figure 10. It can be observed that the two force based estimators performs similar in the precision measure as well, seen over all the test cases. It should be noticed that the actual outcome of the precision measure is highly dependent on the specific force utilization of the test case. For test cases where force excitation does not exceed the required level to obtain a confidence indication, the measure is not computed. Observe that this is a property of the test case and not the estimators.

The correctness measure

The result of the correctness measure can be found in the upper plot of Figure 10. It can be observed that the two force based estimators performs similar regarding the correctness measure. Road eye outperforms the direct approach based methods.

The force-utilization-needed measure

The force utilization needed measure, see upper plot in Figure 11, is only a measure for estimators based on direct approaches and there is hence no computed values for the Road eye estimator. The force based estimators performs similar also for this measure. The lack of value here corresponds to, analogously to the situation for the precision measure, a test case where there are not sufficient tire forces to obtain a valid estimate. This is also a property of the test case and not a performance weakness of the estimators.

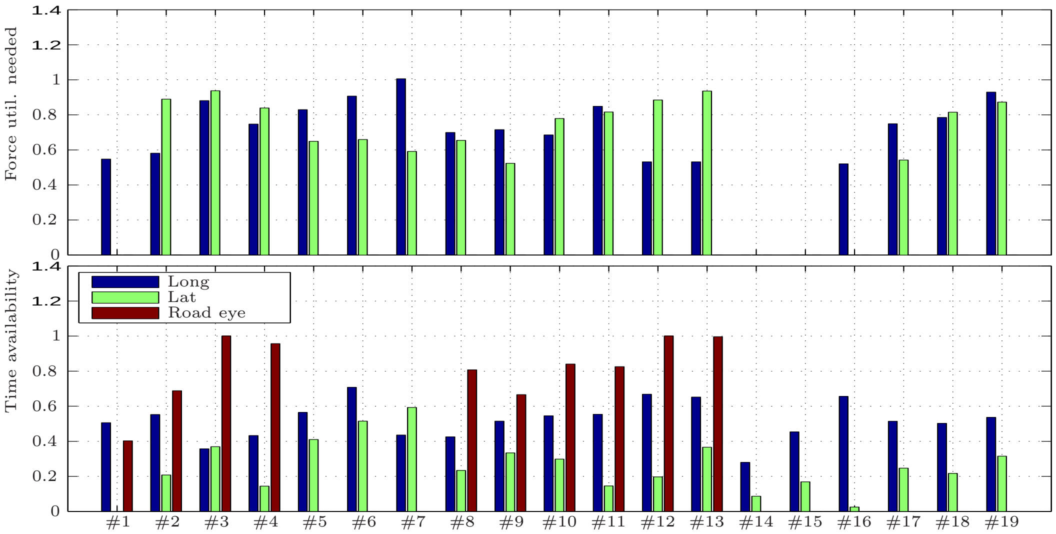


Figure 11: The Availability measures: the force needed (top) and the time availability (bottom).

Table 2: Robustness measure for the two tire force based (direct approach) estimators.

	Precision		**Correctness**	
Inflation Pressure	High	Low	High	Low
Longitudinal	0.41	0.42	0.95	0.95
Lateral	0.33	0.25	0.79	0.70

The time-availability measure

The time availability measure is depict in the lower plot of Figure 11. This measure is very sensitive to the tire force trajectory for estimators based on direct approaches, which makes the comparison hard in this case. The Road eye outperforms the other two estimators in the time availability measure as predicted by the physics behind the approaches.

The robustness measure

The sensitivity to tire inflation pressure is used to illustrate the robustness measure. In test case #11,#12 and #13 contains the nominal case, one case with high tire inflation pressure and one with low inflation pressure. The result is given in Table 2. It can be noticed, see Table 2, that the performance is very similar between the two estimators, and that the correctness is less effected while the precision is more sensitive to the tire inflation pressure.

The rural road drive

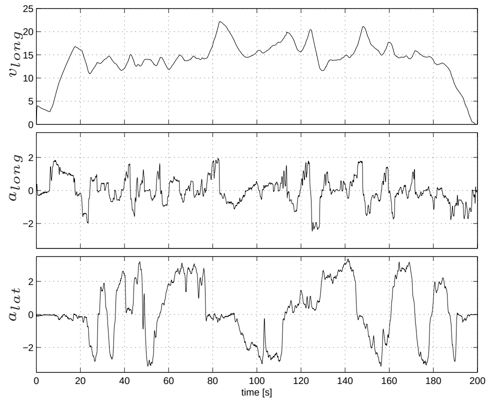


Figure 12: Rural road drive accelerations and speed profile.

The rural road data was recorded on public road. Public roads are most often non-homogeneous w.r.t. tire to road friction which complicates friction reference value. A simple resort is to use the Road eye estimate as reference, as the classification is highly accurate, which disables the possibility to rate the Road eye independently. The rural road speed and acceleration profile is depict in Figure 12. The time availability, which is the most relevant measure in this context, is around 25%.

9 Applications of Friction Estimation

A reliable road friction estimator enables new and enhanced existing applications for vehicle safety during slippery road conditions. The span of the applications are wide from driver information to infrastructure applications such as controlled road maintenance. This variety puts different demands on the road friction estimator that could be defined by the five properties (precision, availability, response time, correctness and robustness), see section 3. Hence, the project have made a list of existing and new road friction applications for evaluation with respect of the defined properties. The main idea is that the evaluation should cover the range of potential applications of friction estimation. The evaluation was performed by the project group including representatives from research and automotive industry with experts in vehicle dynamics, sensor technology, vehicle safety and driver support appications.

The evaluation may serve as a guideline for chosing the appropriate friction estimation technology to best serve specific applications or vehicle functions.

9.1 Applications

The following generic applications were analysed in this study:

- **Road friction information for the driver (RFID)** This application informs the driver about the current road friction status. It can possibly be combined with a warning function that alerts the driver when there is a risk for slippery conditions. Information may be actuated “gentle” by lights in the dashboard or acoustics or combinations thereof. See for example [23].
- **Road slipperiness warning (RSW)** is a similar function as above but with a more aggressive warning to the driver e.g. haptic or acoustic.
- **Communication with infrastructure (C2I)** This application uses the infrastructure as a carrier, collector and consolidator for the road friction estimated by vehicles. The consolidated road status information may be used to control road maintenance and other road-users. The information is processed in a central and has a turn around time relevant to the road conditions and vehicle dynamics. See[24, 13].

Table 3: Requirement on the road friction estimate. L indicate low, H indicate high and M intermediate requirement. [1]A warning might address higher demands on the preview. [2]Latency is not a problem, but distance error might be. [3]Availability during gentle driving. [4]Preview would add value but is not a requirement.

	Correctness	Time availability	Response time	Robustness	Precision	Preview
RFID	M	H	L	L	L	L[1]
RSW	H	H	M	H	M	L[4]
C2I	M	L	L[2]	M	L	L
ACC	M	M[3]	L	M	L	L
DACC	M	M	L	M	L	H
SCS	H	L	H	L	M	L
ACM	H	M	L	M	M	L

- **Adaptive cruise control (ACC)** is a cruise control that adapts the distance to the vehicle in front automatically adapted on estimated friction.
- **Danger ahead cruise control (DACC)** is a cruise control that considers the road curvature (map and GPS based) and adapts speed based on road friction and the appearance of the road ahead of the vehicle. Speed adapation to potentially dangerous situations ahead (e.g. road crossings, schools) may be enhanced by Danger Ahead Cruise Control (DACC).
- **Stability control functions (SCS)** are functions that enhance stability and driver control of the vehicle. Examples of these are ABS (brake control), ESC (vehicle stability control), TCS (traction control), engine braking control and torque vectoring. For functions controlling the lateral dynamics (like ESC), the potential improvement is to introduce side slip estimation. Since all the mentioned SCS functions are dependent on road friction, their performance may be enhanced by road friction estimation.
- **Autonomous collision mitigation (ACM)** Autonomous collision mitigation (ACM) functions such as Collision Mitigation by Braking (CMbB) may be enhanced by information about the road friction. Traditionally these functions assume a road friction coefficient close to one. The road friction estimation may be used to alter the time of intervention, i.e. to make a earlier intervention whenever the road friction is low. This will lead to increased safety during slippery road conditions. See[19].

In addition to the above-mentioned functions, it was only a **Brake Distribution Function (BDF)** which was added when the road friction estimation functions for heavy duty trucks was discussed. This function would then determine the grip of each wheel to determine which wheels that would optimise the deceleration of the vehicle and at the same time spare the brakes as much as possible. Such a function would require a high *time availability* and short *response time* to be of use.

9.2 Requirements

The slippery road condition applications shown in Table 3 are evaluated for low(L), high(H) and intermediate(M) requirements. With preview it is meant that the estimated friction is available in front of the ego vehicle. The other measures are defined in previous section. For

Table 4: Performance of the road friction estimate. L indicate low, H indicate high and M intermediate performance.

	Correctness	Time availability	Response time	Robustenss	Precision	Preview
Direct	M	L	M	M	M	L
Indirect	L	H	H	M	L	M
Integrated	M	H	H	M	M	M

more specific boundaries of the requirements more tests are needed, that was not done within this project. Therefore the requirements are more guidelines than hard boundaries.

There are two different categories of applications; information applications and vehicle applications. The information applications could be divided into two subgroups; driver information and information to other drivers and/or infrastructure. The first and second applications, (RFID, RSW) are examples of driver information applications. To be accepted by a driver the application needs to be continuous, robust and correct, otherwise the driver will ignore the application. These requirements drive the measures *Time availability*, *Robustness* and *Correctness* to be high, for the warning application(RSW), or at least intermediate for the RFID application. Furthermore, information applications can also be used to communicate with infrastructure as C2I. For such application the *Time availability* and *Response time* requirements decreases since the reaction time of the end user increases.

The second category, integrated applications can also be divided into two subgroups: driver aids and vehicle functions. The driver aids applications are the ACC and the DACC. One important feature of these applications are that they are driver controlled, i.e. the driver decides when these applications are turned on. Therefore the main responsibility is on the driver which results in low requirement on the applications, except in the case of DACC and the *Preview* requirement. Without a high requirement on the *Preview* the application has lost it purpose.

The other subgroup, SCS and ACM, are applications that should enhance existing applications as ABS, ESC, TCS and CMbB. The advanced vehicle dynamic applications, ABS, ESC and TCS, have short response times and are crucial as support for the driver. Hence the high requirements on the *Correctness* and *Time response* for the SCS application if it should be incorporated into such applications. The last application, ACM, is an enhancement of the existing function, CMbB, where the tire to friction estimate is incorporated into the breaking distance and therefore needs a high requirement on the correctness measure.

9.3 Discussion

Above several applications have been evaluated for requirements. Within this project three road friction estimators have been developed to provide the information these applications needs. As discussed in section 7 there are pros and cons for the indirect and direct road friction estimators, therefore an evaluation of the performance of the Direct, Indirect and a Integrated method is tabulated in Table 4 as a guideline for which estimator should be used for a certain application. The methods are evaluated for low(L), high(H) and intermediate(M) requirements as the applications. The strength of the Direct methods is that they actually estimate the tire to road friction for a given setup in the vehicle. Hence, the medium evaluation in performance for the *Correctness* and *Precision* measure. The main shortcoming of the Direct methods is the

Time availability. In opposite to the Indirect method which have low evaluation for *Correctness* and *Precision* and high for *Time availability* and *Response time.* Therefore an Integrated road friction estimator using both the Direct and Indirect methods would be best as seen in Table 4.

10 The Future of the Road eye Concept

In the previous RFE project several optical road surface monitoring sensors were investigated. The Road eye,[14, 15], showed most promising performance and was therefore developed further with the intent to become an available product.

10.1 Contacts with Possible Manufacturers of the Road eye

In the RFE project we have successfully demonstrated the potential of the Road eye technique. But as seen from a car manufacturer's view many questions remain to be answered before deciding to go further. Some examples of questions are:

- Can we find a technical solution that will work in all possible environments?
- What is the best location and mounting in the vehicle?
- What is the production cost per unit?

All of the answers to these questions can not be given within the project and in some cases they are outside the scope of the RFE project.

To investigate the interest for industrialisation of the Road eye system, we have active getting into touch with several companies. The project and the Road eye product have been introduced and a few questions have been asked:

- Are you interested in participating in the project?
- Are you interested in the Road eye product?

The answers from the different companies are very similar. They are all very interested in the product and the technique. But before they decide to invest money in the product they need to know that a car manufacturer has made some kind of commitment to the technique. Some of the companies were interested in doing work, but on consultancy basis.

10.2 Productification Issues within the Project

As a result of the described attitude from the companies we decided to answer a reasonable part of the questions within the project. Here are, in short with reference to the questions above, some results of that work.

- After manufacturing the sensors for the tests in Arjeplog a new casing in Aluminum was finished. Even if that solution is too expensive to manufacture in large volumes it is a step forward because the work with it has taken us nearer to a solution that works in large volume production. With a such encapsulation the sensor could be sold on the after market as well, mounting it afterwards on trucks and cars.
- In the Arjeplog tests the sensors were located in front of a front wheel and ”looking” slightly forward. After coming back to Göteborg and Trollhättan, i.e. after thousands of kilometers on typical Swedish winter roads, it could be seen that the dirt contamination

of the critical surfaces was almost negligible. So localization of the tube in front of the sensor body seems not too bad.

- The cost of the components has gone down dramatically since the first prototypes were made about ten years ago. The main reason is that the price of the lasers used has gone down during the latest years because of large volume demand from the telecom industry. Today the total component cost at 10k to 100k volumes can be estimated to about SEK 300.

10.3 The Future of Road eye Product at Optical Sensors


16.06.2009

Figure 13: Encapsulated Road eye

At Optical sensors we intend to start a production of Road eye sensors for demonstration and research projects. The planned batch size is of the order 10. We are able to handle volumes up to hundreds, which is a batch size certainly smaller than vehicle industry demands but certainly large enough for reducing price and increasing the knowledge. There is also a version of Road eye for roadside mounting available. This sensor can be used for optimization of road maintenance and for automatic setting of speed limits. Two sensors have been tested in Sweden by Svevia [2] and also in other countries with good results. The two versions of Road eye support the development of each other. Production and future use of the produced sensors will contribute to the knowledge about the Road eye sensor.

11 Conclusions and Recommendations

Within this project we have carried out the following:

- Development and enhancement of three friction estimation methods tested during RFE I. Two direct methods and one indirect method. The conclusion of the evaluation of the three estimators is that an integration of all three methods into one estimator would solve some of the shortcomings each method have when used in isolation.
- Development of a methodology to evaluate the performance of road friction estimators. The evaluation is based on measures which are taking into account requirements from both new possible vehicle safety applications and already existing ones. The evaluation is generic which makes it possible to evaluate road friction estimators in a competitive way.
- Evaluation of existing and new vehicle application that could benefit from a road friction estimator. The evaluation was based on the measures developed for evaluation of road friction estimators. The Indirect and Direct methods where also evaluated in the same manner as the applications to give an idea how they fulfilled the requirements.
- Investigation on the possibility of industrialisation of the indirect sensor Road eye. There are several companies that are interested but none so far is willing to take the risk

of development. Though the prototype sensor has developed with respect to size and encapsulation, no significant further step towards mass production was accomplished within the project.

The recommendations from this project are:

- Select a few applications that are expected to have the highest potential in terms of benefits from friction estimation. Develop and test the integrated function in prototype test vehicles. The integrated functions may utilize one or several of the friction estimation techniques developed in this project. The results from the investigation on applications and requirements, as reported Section 9, could serve as a guideline when selecting appropriate estimation methods for the applications.
- Develop an after market retrofit variant of the Road eye concept for driver information, driver warning or communication to infrastructure (RFID, RSW or C2I applications in Section 9). The potential market are special vehicles and customers with specific needs.
- Include software for direct friction estimation in vehicles in order to communicate road status to other vehicles and road infrastructure. Systems for cooperative vehicle and road infrastructure is emerging technology. For examples see SAFESPOT [1] and SRIS [24]. Road friction has been identified as important information to communicate to other road users, with a high potential to increase safety. Direct methods for friction estimation are suitable for these kind of applications since they do not require additional sensors and thus, they can be applied with small additional cost. The limited availability for direct methods, may not be a severe weakness since measurements may be collected from many vehicles.

12 Acknowledgments

The project is to a great extent financed by IVSS. This financial support is gratefully acknowledged. Without IVSS, this project would likely not have been initiated. The IVSS program has not only resulted in several ways of estimating the tire to road friction, but also a fruitful network between several companies, institutes and universities.

13 Publications

The project has lead to a series of publications of which some of them are public, some internal and some in the form of patent applications. The publications are listed below:

13.1 Public

[a1] B. Schofield. *Model-Based Vehicle Dynamics Control for Active Safety.* PhD thesis, Department of Automatic Control, Lund University, Sweden, September 2008

[a2] J. Svendenius, M. Gäfvert, F. Bruzelius, and J. Hultén. Experimental validation of the brush tire model. *Tire Science and Technology, TSTCA*, 37(2):122–137, june 2009

[a3] F. Bruzelius, M. Hjort, J. Svendenius, and S. Solyom. A simple combined slip tire model for use in tire to road friction estimation applications. *Vehicle System Dynamics*, 2009. submitted

[a4] F. Bruzelius, J. Svendenius, S. Yngve, J. Casselgren, J. Rönnberg, G. Olsson, and M. Andersson. Evaluation of tire to road friction estimators, test methods and metrics. *International Journal of Vehicle Systems Modelling and Testing*, 2010. In Press

[a5] J. Casselgren. *Road surface characterization using near infrared spectroscopy.* PhD thesis, Luleå University of Technology, 2011. To be published

[a6] S. Löfving. Road eye – a laser sensor for monitoring road state. Internet, 2009. http://opticalsensors.se/roadeye.html

13.2 Internal

[b1] F. Bruzelius. A simple analysis of the lateral tire force estimates and verification towards measurements. Technical report, Volvo Technology, 2008

[b2] J. Rönnberg, J. Svendenius, S. Solyom, and F. Bruzelius. Road friction estimation ii - project internal report - longitudinal friction estimation. Technical report, IVSS, 2009

[b3] J. Svendenius. Validation of the brush model towards vti-measurement data recorded on gravel during the winter 2007/2008. Technical report, IVSS, Sweden, May 2008. RFE-project

13.3 Patents

[c1] F Bruzelius, H. Hultén, S. Solyom, J. Svendenius, and M. Gäfvert. Vehicle-to-road contact estimation. Patent application, June 2008. Assignee: Haldex & Ford

[c2] F. Bruzelius and J. Casselgren. Combining optical road classification with friction estimation ... Patent application, September? 2009. Assignee:Volvo

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Postal address: IVSS/Swedish Road Administration, SE-781 87 Borlänge, Sweden
Street address: IVSS/Swedish Road Administration, NAVET, Lindholmspiren 5, Gothenburg, Sweden
Phone: +46 (0)771 119 119
ivss@vv.se
`www.ivss.se`